APPLICATION OF PLASMA EROSION OPENING SWITCHES TO HIGH POWER ACCELERATORS FOR PULSE COMPRESSION AND POWER MULTIPLICATION[†]

R. A. Meger, J. R. Boller, D. Colombant, R. J. Commisso[(a)],
G. Cooperstein, Shyke A. Goldstein[(a)], R. Kulsrud[(a)] J. M. Neri[(a)],
W. F. Oliphant, P. F. Ottinger[(a)], T. J. Renk[(b)], J. D. Shipman, Jr.[(c)],
S. J. Stephanakis, F. C. Young, and B. V. Weber[(a)]

Naval Research Laboratory
Washington, DC 20375

Summary

A new vacuum opening switch called a Plasma Erosion Opening Switch is described. A model of its operation is presented and the energy efficiency of such a switch is discussed. Recent high power experiments on the Gamble II accelerator are described and compared to previous experiments.

Introduction

There has been considerable interest in recent years in using inductive storage techniques for pulsed power applications. Some of the advantages that inductive generators have over the more conventional capacitive systems include higher final stage energy density for higher power and smaller generators, lower insulator stress, faster pulse risetime, and the possibility of shorter pulse length. In an inductive store generator the energy is stored in the form of magnetic field energy near the load. A switch first conducts current while the inductor is charged then opens to release the energy to the load. The length of time that the switch conducts and how fast it opens determines the output voltage for a given load. For applications where high voltage and short pulses are desired the switch must operate in vacuum. The type of switch applicable to a particular system depends on how the system is to be used. The switch used to tailor a pulse by removing prepulse or sharpening the risetime will be different from one designed to compress the pulse. The difficulties assoicated with switching increase as the ratio of the conduction time (charging time of the inductor) to the opening time increases. The faster a particular switch opens to an impedance much greater than the load impedance, the shorter the output pulse and the higher its power can be.

Several different types of fast opening switches have been investigated. Some examples are the e-beam controlled switch[1], the Plasma-Flow switch[2], the Dense Plasma Focus switch[3], and the Reflex Switch[4]. These switches can handle currents of up to several megamps, voltages of several hundred kilovolts, have conduction times ranging from milliseconds to hundreds of nanoseconds, and switching times ranging from microseconds down to tens of nanoseconds. They all use different opening techniques. The switch described in this paper, called the Plasma Erosion Opening Switch (PEOS), operates in a different manner from those mentioned above.[5] It can be used to produce megavolt voltages and can conduct megampere currents for up to 100 ns with opening times of ~ 10 ns. Because of the short conduction time and relatively fast opening time this switch is primarily applicable to the output stage of a pulsed power system. It is ideal for upgrading existing conventional generators to higher power and shorter pulse length.

The switch uses a plasma column injected before the generator is fired. Two dimensional effects from the self magnetic fields associated with the current in the switch itself alter the electron flow and open the switch. The conduction and opening times can be tuned by changing the switch geometry and by altering the injected plasma. Experimental measurements have shown the switch resistance to change from less than 10^{-2}

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Ohms to more than 20 Ohms in 10-20 ns. The low impedance conduction phase has been observed to last for up to 100 ns before the switch opens. This work represents an extension of work performed at Sandia National Laboratory[6,7] where it was used for prepulse suppression and risetime sharpening.

A qualitative description of the PEOS operation which agrees with the experimental results is given in this paper followed by a discussion of the energy efficiency of such switches. Then the Gamble II experiment is described and preliminary results of recent experiments are discussed. This data is then compared with earlier experiments at lower power levels.

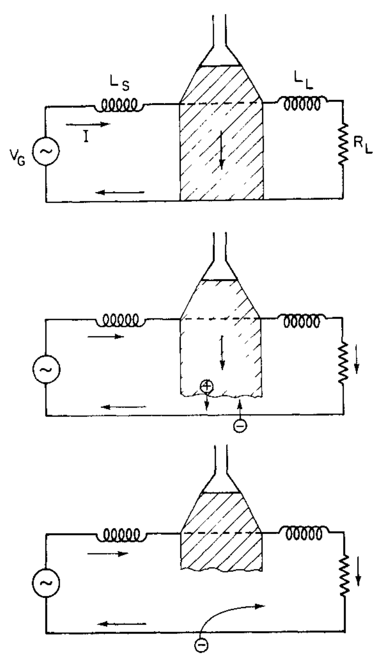

Fig. 1. Schematic representation of the PEOS operation.

PEOS Operation

Operation of the PEOS is illustrated in Fig. 1. The system consists of an inductor followed by a switching section which has been mounted on the output end of a conventional pulse power generator. The generator charges the vacuum inductor with current through the initially closed switch. Downstream of the switch is a short low inductance feed section followed by a load impedance. The storage inductor is matched to the generator to insure optimum energy transfer. The output or load inductance is small compared to the storage inductance to minimize energy losses and minimize the risetime of the load current. The switch consists of a carbon plasma (primarily C^{2+} and C^{3+}) injected through the anode toward the cathode with a drift velocity of 5-10 cm/μs and a full-width-at-half-maximum as measured by a Faraday cup charge collector of ~ 2 μs . The carbon plasma guns are of a type developed at Sandia National Laboratory.[8] The guns are fired several microseconds before the generator is fired to allow the plasma time to drift into the switch region. The 100 ns long input voltage pulse is short relative to the timescale of the injected plasma.

When the generator is fired it starts to charge the inductor by drawing current through the plasma. A sheath or double layer then forms somewhere in the plasma and rapidly moves to the cathode resulting in an electric field near the cathode surface. When the field is high enough (~ 10^7 V/cm) some process such as whisker explosion produces a dense plasma on the cathode surface.[9] The sheath then acts as a bipolar Child-Langmuir diode with carbon ions from the plasma providing ion current on the plasma side of the sheath and electrons from the cathode plasma providing the electron current on the other side. The electrons carry most of the current across the sheath while the slower ions supply space charge neutralization in the gap. For a carbon plasma the ions carry less than 1% of the total current. The sheath does not open up as long as enough ions cross the plasma/vacuum interface to maintain the bipolar flow. This ion flux is provided by the drift velocity of the injected plasma and the ion thermal motion in the plasma. It allows a large current to pass through the switch at low impedance without opening the sheath and increasing the switch impedance. Experimentally, ion flux densities of up to 40 A/cm^2, as measured with Faraday cups, are injected and can support total current densities of up to 4 kA/cm^2 without opening the sheath.

When the ion current density exceeds the available ion flux, ions are drawn out of the plasma itself, thereby eroding the plasma/vacuum interface and opening the sheath. The impedance of the switch varies as d^2 (d=sheath thickness) so the impedance of the switch increases rapidly as

the plasma is eroded. Sheath opening velocities of 10 cm/μs are possible by this mechanism. When the current in the switch is high enough that the self magnetic field effects become significant, the electrons from the cathode are bent downstream toward the load as they cross the sheath. Due to their traveling along the sheath toward the load they spend more time in the vicinity of the plasma/vacuum interface which enhances the ion flow from the plasma.[10] With the enhanced erosion of the ions the sheath opening velocity increases to as much as 100 cm/μs raising the switch impedance rapidly. In addition since the electrons remain in the sheath region longer, the emission from the cathode is suppressed somewhat which further increases the switch impedance. Finally, when the sheath has opened wide enough, the electrons become magnetically insulated and the current switches to the load. The insulated switch electrons flow downstream toward the load to join the diode electron flow, to be recaptured by the conductor, or to be lost to the anode due to instabilities in the flow.

The conduction phase of the switch depends on the plasma density and the risetime of the current through the switch and can last for ~ 100 ns. The erosion and enhanced erosion phases depend on the density and the geometry of the switch and can be as short as several ns. The final insulation phase can begin on a nanosecond timescale and will continue until the switch electrons are no longer magnetically insulated.

This model of the switch operation is very simple. It ignores magnetic pressure and other effects which may play a role in the switch operation. A computer code[11] based on this model does show reasonable agreement with the experimental results in both absolute numbers and in scaling dependencies.

Switch Losses and Power Gain

To investigate the energy efficiency and power gain from an opening switch system such as described in the last section a transmission line code calculation was performed. The circuit is shown in Fig. 2. The input voltage waveform approximated a real 1 MV peak open circuit waveform and the line elements were similar to those of the Gamble II experiment to be

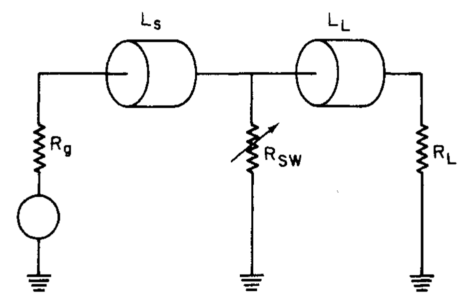

Fig. 2. Schematic of the circuit used in the transmission line code.

described later in this paper. The switch model used ramped the switch impedance from 0 to 100 Ohms over 10 ns. The switch was timed to open at the peak inductor current simulating the ideal switching case. The results of this study are general and serve as an illustration of the energetics involved with the opening switch.

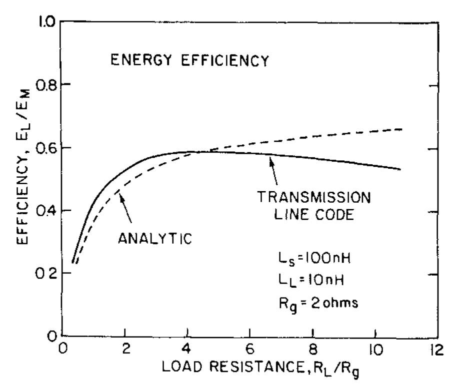

Fig. 3. Energy efficiency versus load resistance for an opening switch near the load.

Figures 3 and 4 show some of the results. Figure 3 plots the efficiency as a function of the load resistance normalized to the generator resistance. The efficiency is defined as the energy deposited in the load resistance with the opening switch and inductive store section, normalized to the energy into an ideal load matched to the generator impedance without the added inductive store section. The energies are integrated over time and are not sensitive to the

width of the output pulse or its peak power. The figure shows that for load impedances below the generator impedance the coupling efficiency is low. As the load impedance increases the efficiency increases to a peak of approximately 60% where it plateaus for a large range of output impedances. The losses demonstrated in this figure can be divided into several sources. First the transfer of the generator energy into inductive energy is 80% efficient under optimum conditions, second the switch itself absorbs 10-20% of the energy during the opening process depending on the output inductance and load resistance, and finally some of the energy is reflected back into the accelerator after the switch is opened due to mismatches between the switch and inductor impedances. The output inductance, L_L, also affects the energy efficiency but the effect scales as $L_s/(L_s+L_L)$ which for $L_L \ll L_s$ is small.

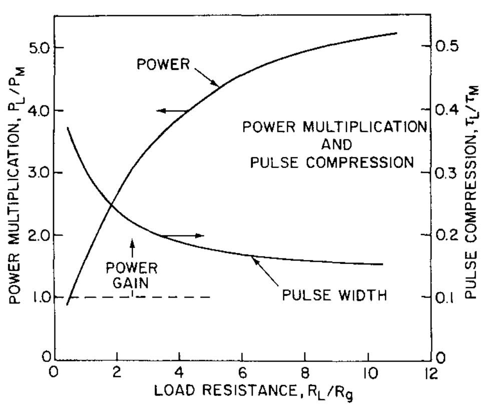

Fig. 4. Power gain and pulse compression with an opening switch. Peak power gain with the switch is normalized to the matched load peak power. Pulse compression is the FWHM of the output voltage with the switch normalized to the matched load case.

Figure 4 shows the power gain and pulse compression resulting from using the fast opening switch. This voltage, and therefore power, multiplication will occur as long as the switch opening time is short relative to the discharge time of the inductor through the load. Power gains of up to 5X the matched load power are shown in this figure for load resistances of 10X the generator impedance. The power gain is insensitive to the output inductance as long as the downstream inductor impedance is comparable to the load impedance. The second curve shows how the pulse width has decreased as the load resistance is increased. As the pulse length gets shorter the switching speed becomes more important, ultimately limiting both the power gain and the pulse compression. If the switch were instantaneous the ultimate pulse length would be twice the electrical length of the inductive store region. The switch must also open to a much higher impedance than the load impedance or the switch losses absorb a larger fraction of the energy.

These figures illustrate the energy efficiency and power gains that are possible with a fast opening switch. The circuit used in the transmission line code analysis approximated the experimental arrangement and the switch opening time used in the code was close to the measured switch opening time.

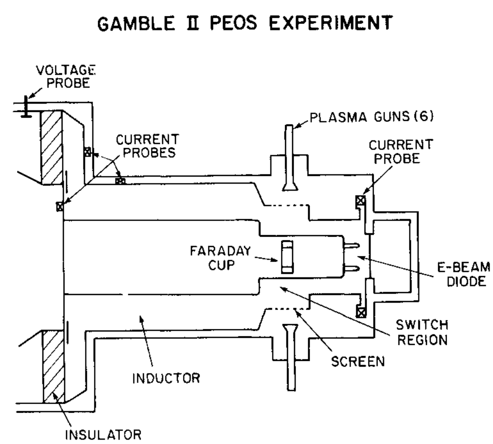

Fig. 5. Schematic of the Gamble II experiment.

Gamble II Experiments

Experiments on the PEOS have been reported previously on the NRL Gamble I generator.[5] The Gamble II experiment described here, like the earlier Gamble I experiment, incorporated an inductor between the generator and the switch. Similar types of switches without inductors have been investigated elsewhere.[6,12,13] Figure 5 shows a cross sectional view of the Gamble II experiment. The output of the Gamble II generator was fed through a radial dielectric vacuum interface into a 60-cm long coaxial inductor with

17.8-cm diam. inner and 30-cm diam. outer conductor giving a 32-ohm vacuum impedance. This 60-nH inductor along with the 40-nH insulator section form the 100-nH, 3-ns long, storage inductor. At the end of the inductor section the inner conductor was stepped down to 12.4-cm diam. in the switch region. Plasma was injected by six carbon plasma guns through a cylindrical set of rods which formed the 23-cm diam. outer conductor in the switch region. The guns produced peak charge flux densities equivalent to 40 A/cm^2 traveling at ~ 7 cm/μs near the inner conductor as measured by Faraday cups within the structure. The six gun injection provided nearly uniform radial plasma flow. Downstream of the switch was a 15-cm long coaxial section with the same cathode radius as in the switch region and a 17-cm diam. outer conductor. A 6-cm diam. cylindrical cathode was placed at the end of the inner conductor. Gaps of 0.5 cm to 1.5 cm between the stainless steel cathode tip and the thin anode foil were used to provide a diode load impedance of between 5 and 15 Ohms. Diagnostics included various dB/dt and Rogowski coil current monitors both upstream (generator side) and downstream (load side) of the switch. Voltage was measured in the water just upstream of the dielectric interface of the generator and voltages on the switch and load were derived using LdI/dt corrections to the measured voltage.

The plasma guns were fired approximately 2 μs before the accelerator pulse depending on the radial location of the plasma guns. The plasma density was altered with screen filters or by moving the guns radially. The generator was fired near the peak of the faraday cup signals and the plasma density adjusted for optimum switching.

Figure 6 shows some results from the Gamble II experiment where the inner conductor was pulsed negative. The Gamble II Marx generator was charged to 35 kV out of a possible charge of 50 kV giving an open circuit voltage peak of 2.9 MV. The insulator voltage as shown in the figure has a maximum of 1.9 MV. The inductor current reaches 650 kA just as the switch starts to open. Computer modeling and experimental tests show that for a short circuit at the switch location the maximum current in the inductor would be 1 MA with its peak at T=110 ns. The inductor current passes through the switch for 60 ns before current is measured through the load. The load current initially shows a rapid rise ($dI/dt \sim 3\times10^{13}$ A/s) starting at T = 90 ns which after 10 ns appears to slow down reaching its peak of 420 kA at T=115 ns. The switch voltage, $V_S=V_I-LdI/dt$, is compared with the insulator voltage in the figure. The diode voltage is slightly lower than this due to the output inductance. The switch voltage has a peak of 3.0 MV at T=108 ns. The excess voltage is due to the negative dI/dt in the inductor and represents the extraction of the inductively

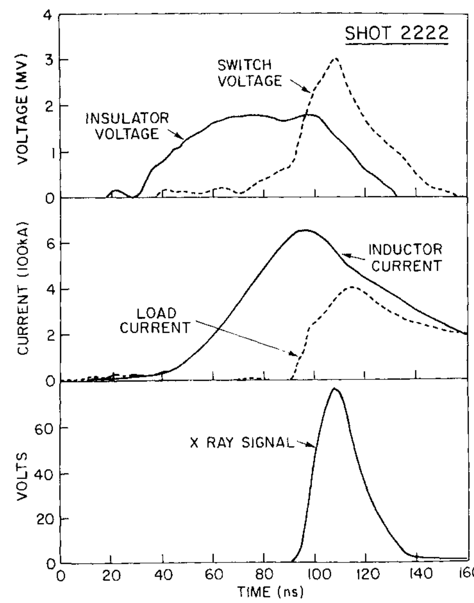

Fig. 6. Results from the Gamble II PEOS experiment.

stored energy through the load impedance. The early time foot on the voltage pulse represents errors in the inductive correction due to vacuum electron flow in the inductor and diode sections as well as an IdL/dt term which is neglected in the correction. The inductance is changing since the relatively tenuous switch plasma ($n_i \sim 10^{13}$ cm^{-3}) is accelerated downstream by the $\underline{J} \times \underline{B}$ forces due to the current driven in the switch. This effect only becomes significant after the current has been present for ~ 50 ns. No voltage appears across the load until the switch actually starts to open as shown by the x-ray signal from the diode region. The pulse shortening effect is also evident from the 20 ns full-width-at-half-maximum (FWHM) of the x-ray signal. Without the opening switch the x-ray signal is smaller in amplitude and has a FWHM of

~50 ns.

The power into the switch peaks at 1.9 TW at T= 100 ns. This compares with a peak power of ~1 TW into a matched load. The power into the load is somewhat lower due to the lower current on the downstream side of the switch. This loss of current is believed to be due to a loss of magnetic insulation just downstream of the switch. Work is in progress to determine the origin of these losses and to correct them.

A rough estimate of how fast the switch is opening can be made assuming the switch opens at the peak current of I = 650 kA. If the switch is magnetically insulated at this time then the switch current must have exceeded the critical current, $I_c = 8.5\times10^3(\gamma^2-1)^{1/2}$ R/d amp, where γ is the relativistic gamma factor of the electrons, R is the cathode radius, and d is the sheath thickness or gap at the time of opening. This gives a gap of ~0.6 cm assuming that γ ~7 at the peak switch voltage. The switch opening time is ~10 ns which gives an average opening velocity of 60 cm/μs which is in reasonable agreement with theoretical predictions.[11]

The switch opening on this shot began somewhat early when the generator was still feeding energy to the inductor. The load was being driven directly by the accelerator during this time until the generator pulse ended. This effect widened the output voltage pulse and lowered the output power. The switch can conduct current for a longer time but the IdL/dt voltage developed due to the plasma acceleration limits the peak current in the inductor. Changes in the switch geometry are necessary to counter this effect and allow switching to occur near the peak current. Even with the early opening these results show power multiplication and pulse compression.

Many such shots have been taken with different plasma densities and relative plasma/generator timings. In general the conduction time depends on how much plasma is in the switch region. Early generator firing sharpens the risetime of the voltage pulse with very little inductive storage. Late firing (> 1 μ s after peak Faraday cup signal) acts as if more plasma were present than inferred by the Faraday cup. This is attributed to a stationary background plasma filling the switch region as has been measured with electric probes and indirectly with spectroscopic techniques.[14]

Scaling of Gamble II Results

The Gamble II experiment discussed in the previous section was in many respects a scale up of the Gamble I experiment.[5] The Gamble II generator is a higher power version of the Gamble I generator with the same 2 Ohm output impedance. The pulse lengths are both 100 ns with twice the voltage and current available on the Gamble II generator. Both generators have radial insulators with output inductances of 30-40 nH. The two experiments differed in vacuum impedance and electrical length of the inductor section. The Gamble I experiment had a 90-Ohm impedance inductor with 1-ns electrical length while the Gamble II experiment used a 32-Ohm inductor with 2-ns length. This gave total inductances of 150 nH and 100 nH respectively when the insulator inductance was included. The Gamble II experiment used 6 guns and a switch area of 180 cm^2 while the Gamble I experiment used 3 guns and a 75 cm^2 switch area. The injected plasma density in both experiments was the same. Table 1 shows a comparison of the results from the two experiments. Switch conduction times for the two experiments were both approximately 60 ns and the peak currents were 250 and 650 kA respectively due to the higher driver voltage from the Gamble II generator. At the time the switch started to open the inductors were charged to 5 kJ and 20 kJ respectively. In both experiments the switch appeared to open in ~ 10 ns producing switch voltages of 1.4 MV and 3.0 MV on Gamble I and II respectively. This gives a voltage multiplication

TABLE I

	GAMBLE I	GAMBLE II
Store Inductance	150 nH	100 nH
Open Circuit Voltage	1.0 MV	2.9 MV
Matched Load Voltage	0.6 MV	1.5 MV
Inductor Current	250 kA	650 kA
Inductor Energy	5 kJ	20 kJ
Opening Time	10 ns	10 ns
Switch Voltage	1.4 MV	3.0 MV
Voltage Multiplication	2.3X	2.0X
Pulse Compression	3X	3X

of a factor of ~ 2 relative to the matched load voltage in both cases. The pulse compression was a factor of 3 in both experiments.

This comparison shows that the two experiments did not produce markedly different results except in the magnitude of the current switched and the peak voltages. Analytic modeling of the switching process shows that the opening depends strongly on the magnetic field near the cathode surface. In this case both experiments had ~ 20 kG near the cathode at the time the switch opened and produced similar opening characteristics in agreement with this theory. In general these results show that the switch operates in a similar manner over a wide range (250-650 kA) of currents. The higher currents were handled by the use of larger area plasma without degradation of the switch opening process.

Conclusions

This paper discussed the present understanding of the Plasma Erosion Opening Switch operation. It presented a simple model of the switch operation which is consistent with experiments. Some calculations of energy efficiency for the switch showed that the switch efficiency is dependent on the output inductance and load impedance but can be made relatively efficient if these values are chosen properly. The computer code work also showed that power multiplications of factors of 5 are possible with pulse compressions of factors of 6 for high impedances. The Gamble II experimental results were presented which showed the switch to operate at the 3 MV, 650 kA level and the similarities to the previous experiments on Gamble I were discussed. In general the switch has been tested at MA current levels and both pulse compression and voltage multiplication demonstrated.

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(a) Jaycor, Alexandria, VA. 22305

(b) National Research Council Associate.

(c) Sachs/Freeman Assoc., Bowie, MD. 20715

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